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INTEGRATED OPTICAL LOGIC GATES. A DEMONSTRATION OF FOUR OPTICAL--ETC(U)
MAY 80 M J TAYLOR, E R SCHUMACHER
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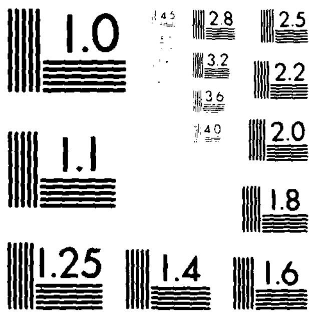

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INTEGRATED OPTICAL LOGIC GATES

A demonstration of four optical logic functions

MJ Taylor
ER Schumacher

6 May 1980

Independent Research Report
December 1977 to September 1978

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An optical NOT gate has been demonstrated, exhibiting close to 100% modulation and requiring a minimum of 1.2 V for switching between states. An optical AND gate has been demonstrated, using two interferometric intensity modulators in series. A device functioning as either an optical EXCLUSIVE OR gate or an even parity generator has been demonstrated, also exhibiting nearly 100% modulation. Lithium niobate cleaving and polishing techniques were examined, indicating further research is required in this area.

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OBJECTIVES

To develop guided wave electrooptic devices for performing logic functions and computation. To fabricate intensity modulators in lithium niobate using titanium in-diffusion. To examine the operation of the logic functions NOT, AND, EXCLUSIVE OR, and parity generation fabricated above.

RESULTS

1. An optical NOT gate has been demonstrated, exhibiting close to 100% modulation and requiring a minimum of 1.2 V for switching between states.

2. An optical AND gate has been demonstrated, using two interferometric intensity modulators in series.

3. A device functioning as either an optical EXCLUSIVE OR gate or an even parity generator has been demonstrated, also exhibiting nearly 100% modulation.

4. Lithium niobate cleaving and polishing techniques were examined, indicating further research is required in this area.

RECOMMENDATIONS

1. Perform further studies to produce single mode waveguides in both TE and TM directions. (Polarization independent devices.)

2. Pursue further research in the area of out-diffusion in lithium niobate. Such information could help make devices operating in the TE-mode (which requires less voltage for phase shifting) exhibit greater depths of modulation than are now being observed.

3. Redesign electrodes to require less voltage, and increase electrical efficiency of devices.

4. Examine losses at corner bends and devise new structures that are less lossy. Severe losses are experienced at angles greater than 2 or 3°, which hinders the operation of more complex structures.

5. Investigate edge finishing techniques on $LiNbO_3$ waveguides, both cleaving and polishing. Investigate a variety of polishing techniques, including diamond finishing.

CONTENTS

ILLUSTRATIONS

INTRODUCTION

Integrated and Fiber Optics Technology has great potential in such areas as communications, signal processing, data transmission, telecommunications, and high-speed computers. An integrated optical system would be lightweight, exhibit low crosstalk, and tend to be immune to electromagnetic interference. It would also be capable of high switching speeds and rapid parallel computation. One important branch of this technology is integrated optical devices. This includes guided wave optical modulators, switches,[1] logic gates,[2] binary adders, and analog-to-digital (A/D) converters.[3,4]

This report describes the demonstration of four optical logic functions. Three optical logic gates (AND, NOT, and EXCLUSIVE OR) and an even parity generator were fabricated in Y-cut $LiNbO_3$ by titanium in-diffusion. Using end-fire coupling, the optical waveguides were excited with a polarized He–Ne laser source. All of the devices are based on the interferometric modulator.[1] As such, they each require a π radian phase shift for switching. In one case, a maximum of 25 π radian phase shifts was observed for 31-V P-P input power, indicating that a minimum of 1.2 V is required for one π radian phase shift. Up to 100% modulation was observed in some devices.

THEORY

The optical logic gates investigated are comprised of one or more interferometric modulators[1,5-7] (figure 1) and a unique electrode set[2] (figure 2). The interferometric modulator operates as follows. The device is designed such that light entering the waveguide is equally split between the two arms of the branch. With no applied voltage, the optical paths followed by the two light beams are equal and the light recombines in phase where the two sections merge into one. Because of the electrooptic effect in $LiNbO_3$, the optical path length in one arm of the modulator can be changed, independent of the other, by applying a voltage across the waveguide. Application of the proper voltage will produce a π radian difference in the two path lengths, causing the two beams to destructively interfere when they recombine. The light is then lost in the substrate and no light emerges from the exit waveguide.

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[1] Martin, WE, A New Waveguide Switch/Modulator for Integrated Optics, Appl Phys Lett, vol 26, p 562-564, May 1975.

[2] Taylor, HF, Guided Wave Electrooptic Devices for Logic and Computation, Appl Opt, vol 17, p 1493-1498, May 1978.

[3] NELC TR 2013, Fiber Optics and Integrated Optics Techniques for Signal Processing by GM Dillard, BR Hunt and HF Taylor, February 1977.

[4] Taylor, HF, Taylor, MJ and Bauer, PW, Electro-Optic Analog-to-Digital Conversion Using Channel Waveguide Modulators, Appl Phys Lett, vol 32, p 559-561, May 1978.

[5] Ohmachi, Y and Noda J, Electro-Optic Light Modulator with Branched Ridge Waveguide, Appl Phys Lett, vol 27, p 544-546, November 1975.

[6] Ranganath, TR and Wang, S, Ti-Diffused $LiNbO_3$ Branched-Waveguide Modulators: Performance and Design, IEEE J Quant Electron, vol QE-13, p 290-295, April 1977.

[7] Sasaki, H, Efficient Intensity Modulation in a Ti-Diffused $LiNbO_3$ Branched Optical Waveguide Device, Electron Lett, vol 13, p 693-694, November 1977.

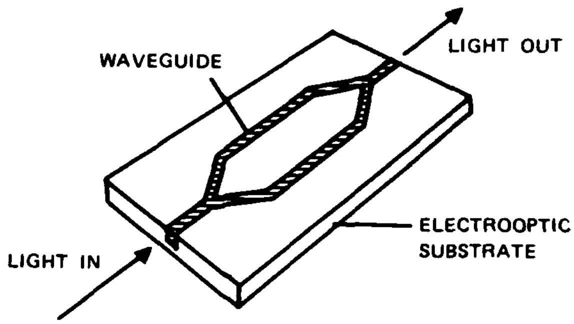
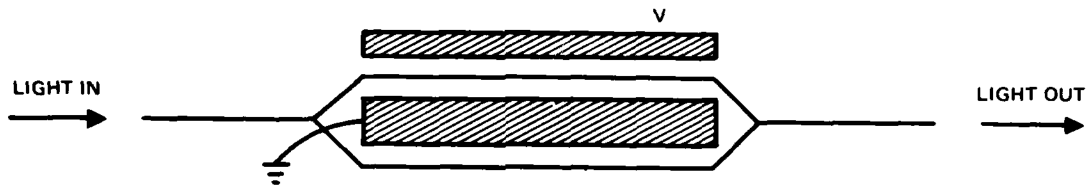
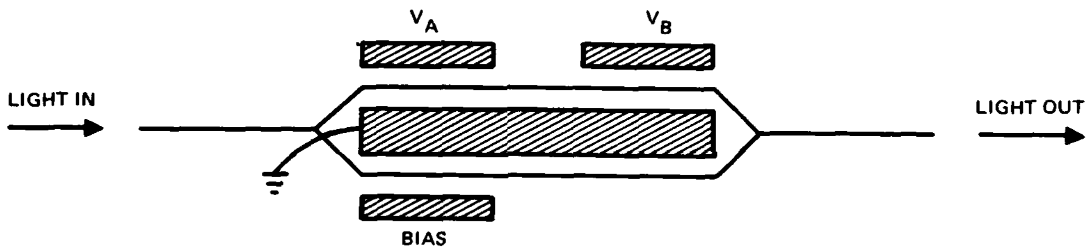


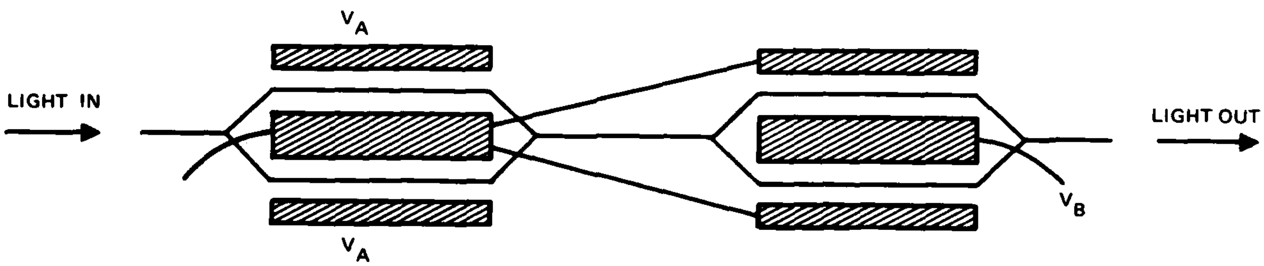
Figure 1. Basic interferometric modulator



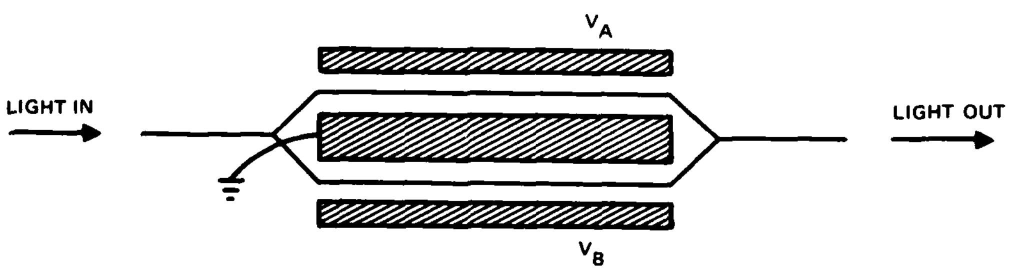
A. NOT gate



B. EXCLUSIVE OR gate



C. AND gate



D. Odd parity generator

Figure 2. Device configuration.

Figure 3 lists the truth tables for the AND, NOT, EXCLUSIVE OR gates and the odd parity generator. The truth table for an even parity generator is identical to the one for the EXCLUSIVE OR gate. A "1" in the voltage column indicates the minimum voltage required to produce a one π radian phase shift between the two arms of the modulator. In the output column, a "1" indicates full light intensity out; a "0" indicates minimum or no light out of the waveguide. By applying voltages to the devices in the manner illustrated in figure 2, the light will recombine either in phase or out of phase at the right-hand branch, functioning as the indicated logic gate.

V	out
0	1
1	0

A. **NOT** gate

V_A	V_B	out
0	0	0
1	0	1
0	1	1
1	1	0

B. **EXCLUSIVE OR** gate

V_A	V_B	out
0	0	0
1	0	0
0	1	0
1	1	1

C. **AND** gate

V_A	V_B	out
0	0	1
1	0	0
0	1	0
1	1	1

D. Odd parity generator

Figure 3. Truth tables.

NOT GATE

The NOT gate (figure 2A) is the simplest logic function under study. With no applied voltage, the two arms recombine in phase to produce full light intensity out. With an applied voltage of sufficient strength to produce a 180° phase shift in one arm, complete light cancellation will occur at the right-hand branch (given that the light intensities from the two arms are equal). Hence, the presence of an electrical signal will prevent a light output and the absence of an electrical signal will allow a light output.

EXCLUSIVE OR GATE

The EXCLUSIVE OR design (figure 2B) requires a bias voltage, ie, one arm of the modulator is set 180° out of phase with the other arm permanently. Applying a single voltage, V_A or V_B , to the other arm returns the modulator to its in-phase condition, allowing light to emerge. If both V_A and V_B are present, one arm experiences a 2 π radian phase shift while the biased arm experiences only a 1 π radian phase shift. The net difference is 1 π radian, and no light emerges from the modulator.

PARITY GENERATOR

An even parity generator is a device which will produce a "0" or "1" so that the sum of the inputs and output will be even.[3] An examination of figure 3B shows the EXCLUSIVE OR truth table to be identical to that of an even parity generator. Therefore, the device shown in figure 2B can be used either as an EXCLUSIVE OR logic gate or an even parity generator, depending upon the application.

An odd parity generator is a device which will produce a "0" or "1" so that sum of the inputs and output will be odd (figure 3D). This device needs no bias (figure 2D). The only condition which will produce full light intensity out is with neither voltage present or with both voltages present. If only V_A or V_B is present, there will be a π radian phase difference between the two arms and cancellation will occur.

AND GATE

The optical AND gate is composed of two interferometric modulators in series (figure 2C). More than two signals can be compared using this logic gate by adding more modulators in series. Like the EXCLUSIVE OR gate, the AND gate is also biased permanently, allowing no light to emerge when no signal voltages are applied. The only condition under which light is allowed to emerge from the right-hand side is when it has recombined in phase after each initial branch. This is true only when both V_A and V_B are present, creating an equal potential across all of the modulator arms.

EXPERIMENTAL PROCEDURES

The experimental section covers three major topics. The first section deals with the actual fabrication of the optical logic gates. The second section gives details of the experimental test set-up. The last section presents the results of each optical logic gate demonstrated.

FABRICATION

The optical logic gates used in this study were fabricated in Y-cut $LiNbO_3$ using titanium in-diffusion.[8] A thin film (400Å ±50Å) of titanium is deposited on the polished face of the crystals. Using standard photolithographic techniques, the waveguide patterns are transferred to the substrate perpendicular to the Z-axis. The unwanted titanium is removed by etching in hydrofluoric acid. The crystals are diffused for four hours in an argon atmosphere at 960°C, followed by one hour in an oxygen atmosphere at the same temperature. After diffusion, the ridge height was found to be nearly double the original thickness, due to oxidation of the titanium film (figure 4). This was true on all waveguides examined. The edges of the crystal are cleaved parallel to the Z-axis and the waveguides examined for mode structure. An aluminum layer (500Å ±50Å) is then deposited and the electrode pattern is transferred as above. Unwanted aluminum is removed using hot phosphoric acid.

Several improvements in fabrication were made during the course of the project. Detailed examination of crystal surfaces at various stages of processing often showed the

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[8] Schmidt, RV and Kaminow, IP, Metal-Diffused Optical Waveguides in $LiNbO_3$, Appl Phys Lett, vol 25, p 458-460, October 1974.

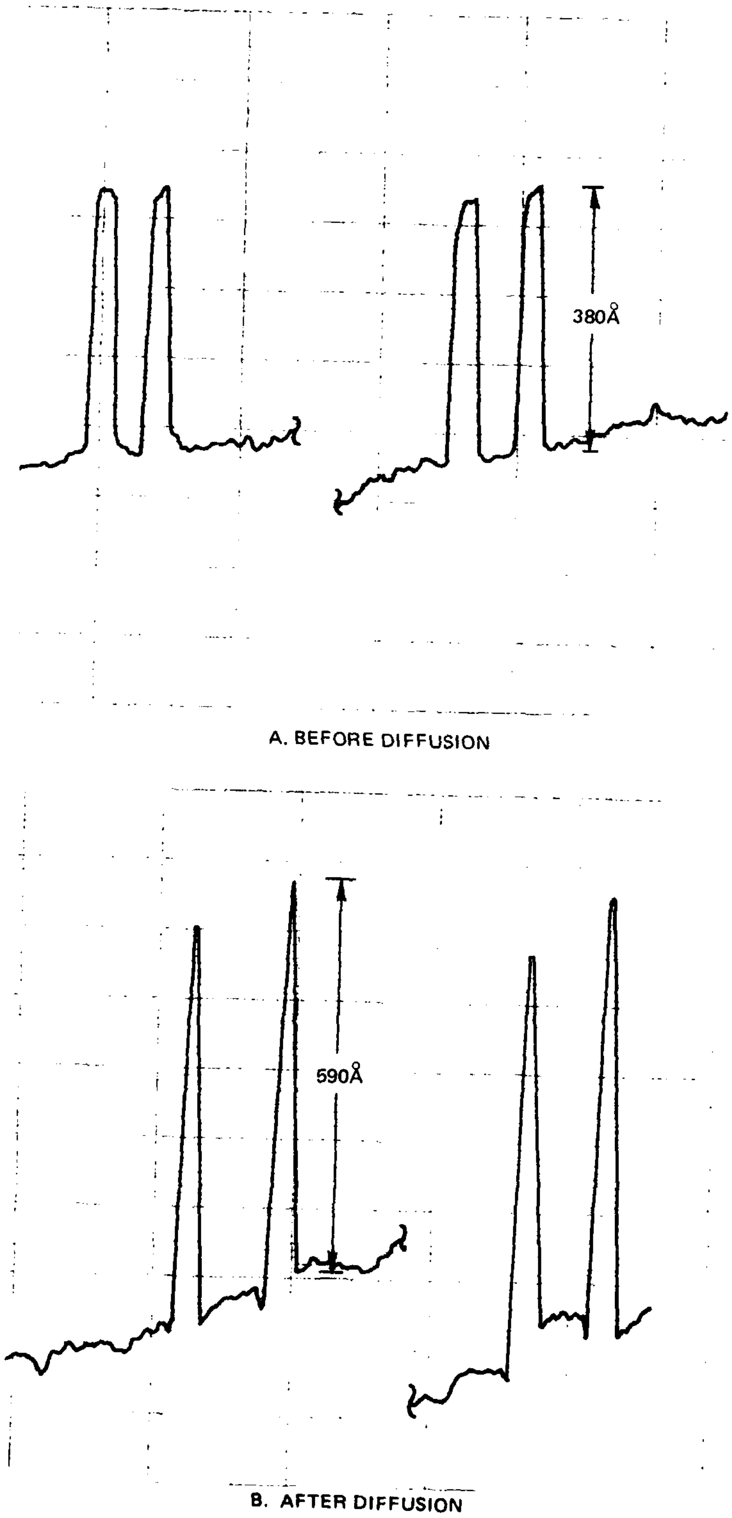

Figure 4. Ridge height.

presence of contamination in the form of spotting, staining or debris. Such a contamination leads to pinholes and voids in finished devices. One source of contamination was from air-borne particles entering the Class 10,000 Clean Room and depositing on substrates during critical processing periods. An improved air filtering system, a different style of protective laboratory clothing, and more limited Clean Room access have been initiated. These steps have helped cut down the amount of floating contamination.

High purity chemicals were also found to be a problem. Examination of evaporating solvents under high magnification showed severe contamination of Electronic Grade material. Microscopic stains were causing poor adhesion of metal films, and pinholes in photoresist layers. All liquid chemicals, except acids, are now being filtered through 0.5 μ PTFE filters prior to use. Solvent drops observed under a microscope now show no signs of residue after evaporation and substrate surfaces appear spot-free after final rinsing.

A characteristic problem with YZ-cut $LiNbO_3$ is the lack of a good cleavage plane. This is extremely important for end-fire coupling and fiber-to-chip coupling. Good edges have been cleaved in the past, using both diamond-tipped scribers and tungsten-carbide scribers. However, the quality of the cleaved edge has not been reproducible from one shipment of crystals to another. Several different cleaving techniques have been investigated. Conical, pyramid, and pentagonal diamond tips have been employed, both manually and in a scribing machine. Saw cuts have also been used to start a cleave. The technique which showed the most promise was edge polishing. Very uniform edges can be produced using this method. There was some chipping around the waveguide regions, however. High-speed diamond tools and diamond polishing compounds may be a way to eliminate this chipping. If so, diamond polishing would provide uniform, clean coupling edges necessary for improved device efficiency.

OPTICAL SET-UP

The present experimental test set-up is diagrammed in figure 5. The excitation light source was a Spectra-Physics Model 120 Stabilite He-Ne (6328Å) laser. The spatial filter consisted of a pinhole and 10X microscope objective. The collecting and focusing objectives were both 40X microscope objectives. The wafer was mounted on a small vacuum chuck to provide rigid support and some vibration isolation. A TIED83 Silicon Avalanche Photodiode, biased at −80 VDC, was used as a detector. Voltages were applied using Micromanipulator tungsten probes. Driving voltages were derived from a Wavetek Model 142 HF VCG

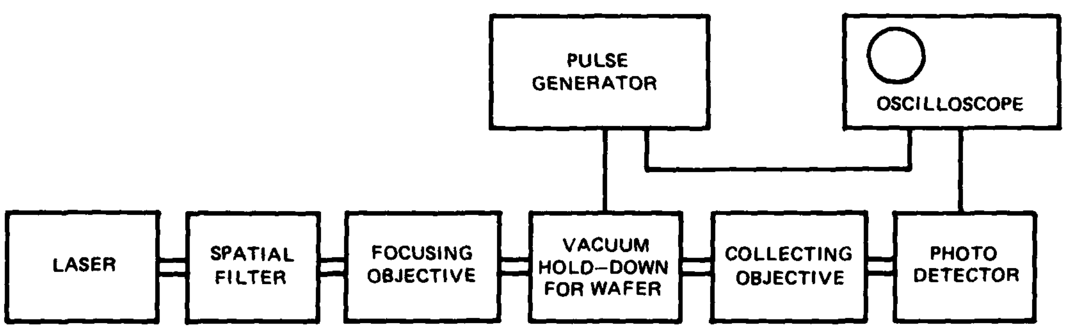

Figure 5. Experimental test set-up.

Generator. Outputs from the detector and function generator were simultaneously displayed on a Tektronix Model 7904 Oscilloscope.

All voltages applied were ac signals at varying frequencies and amplitudes. Bias voltages were also ac inputs. In this experiment, no dc voltage could be used. These tended to set up charges on the crystal and make switching difficult. Voltages on the probes were all taken from one power supply to insure a coherent phase relationship.

LOGIC GATES

NOT Gate

The optical NOT gate was first excited using TM-polarized light (perpendicular to the substrate surface). Figure 6 is a series of photographs showing the NOT gate responding to an increase in amplitude using this polarization. The gate's response is seen to be periodically varying with input amplitude. Approximately every 3 to 5 V the device would experience another 2π radian phase shift. Figure 7 is the same device excited with TE-polarized light (parallel to the substrate surface). Out-diffusion was severe using this polarization. This may account for the modulation depth being much shallower than with the previous orientation.

Close to 100% modulation (±5%, due to oscilloscope accuracy) was observed with this design, requiring only 1.2 V for initial extinction. Up to 25π radian phase shifts were observed in this device for 31-V P-P input (figure 8). Although a greater depth of modulation was observed with TM-excitation (100% vs 75% for TE-excitation), a greater number of phase shifts was observed with TE-polarized light (figure 9). If out-diffusion in this orientation could be eliminated, it would be more efficient since less voltage is required for switching between states. Several techniques for eliminating out-diffusion have been suggested, such as annealing the substrate in $LiNbO_3$ powder either during or after in-diffusion,[9] or by placing chunks of Li_2O upstream during the diffusion process.[10] Neither of these techniques, however, is 100% efficient.

EXCLUSIVE OR Gate

There are four input states in the EXCLUSIVE OR truth table (figure 3B). The first state is with no applied voltages, only a bias voltage. In figure 10 the device, connected as in the first state, is shown switching between states (0, 1). States 2 and 3 are essentially the same, one applied voltage and one grounded electrode. Waveguide output is illustrated in figure 11. Nearly 100% modulation was observed in this trace. The fourth state is with both V_A and V_B present. Figure 12 illustrates the gate's periodic dependence on applied voltage in this case. All of the above photographs were taken using TM-polarized light to excite the waveguide.

The waveguides were multi-mode when excited with TE-polarized light. There was strong mode shifting in the laser and no oscilloscope traces were stable enough to photograph using this polarization. However, responses observed were similar to those shown above.

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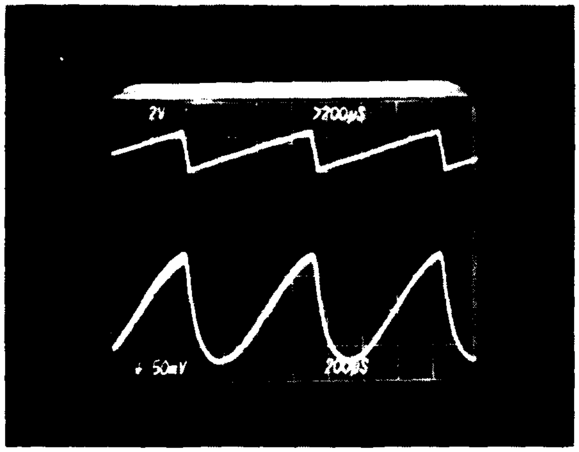
[9] Chen, B and Pastor, A, Elimination of Li_2O Out-diffusion Waveguide in $LiNbO_3$ and $LiTaO_3$, Appl Phys Lett, vol 30, p 570-571, June 1977.

[10] Ranganath, TR and Wang, S, Suppression of Li_2O Out-diffusion from Ti-diffused $LiNbO_3$ Optical Waveguides, Appl Phys Lett, vol 30, p 376-379, April 1977.



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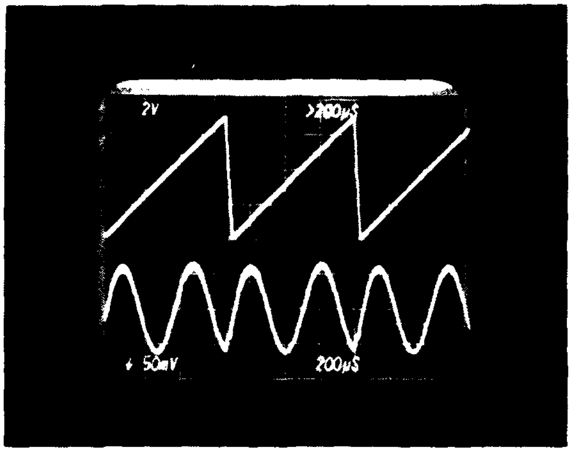

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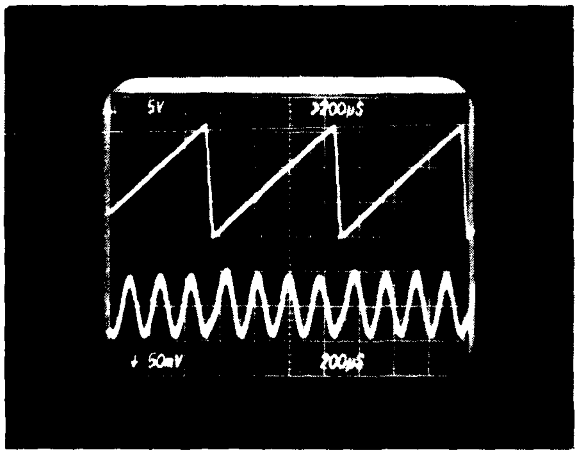

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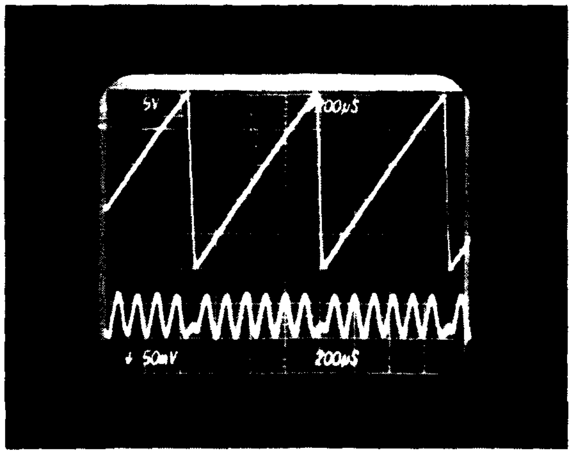

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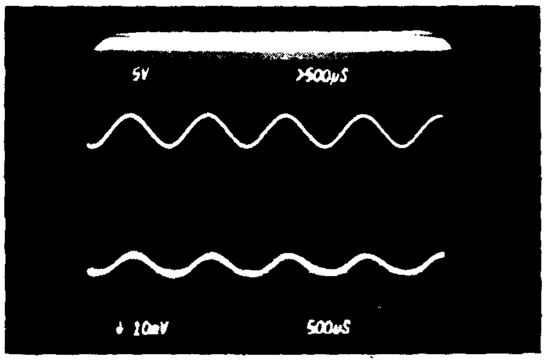
Figure 6. Response of NOT gate to increase in voltage (TM mode).



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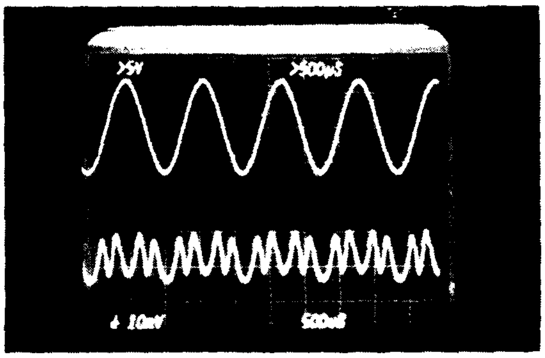

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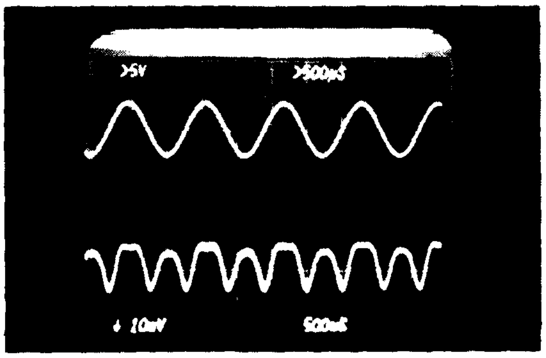

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Figure 7. Response of NOT gate to increase in voltage (TE mode).

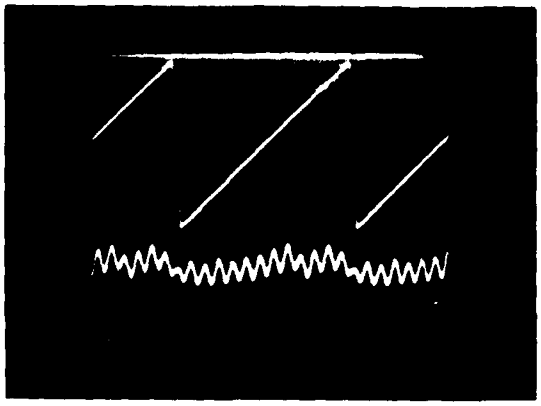


Figure 8. Maximum 25 π radian phase shifts for 31-V P-P input.

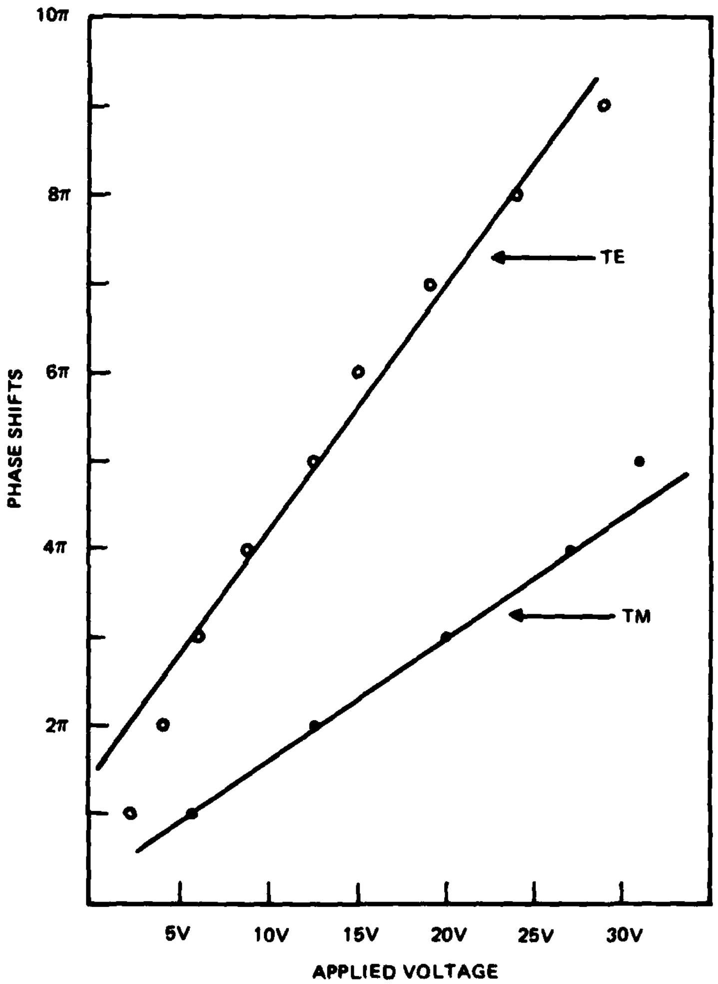


Figure 9. Phase shift vs applied voltage.

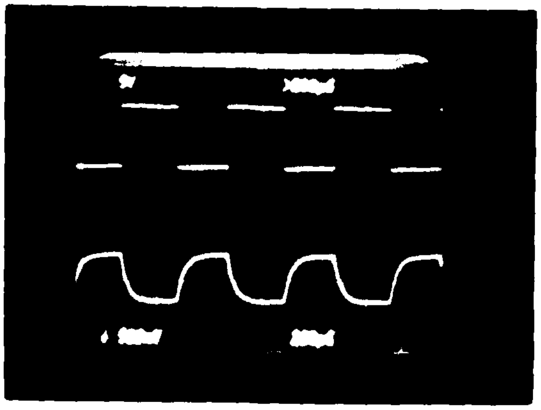


Figure 10. Step 1 of EXCLUSIVE OR gate.

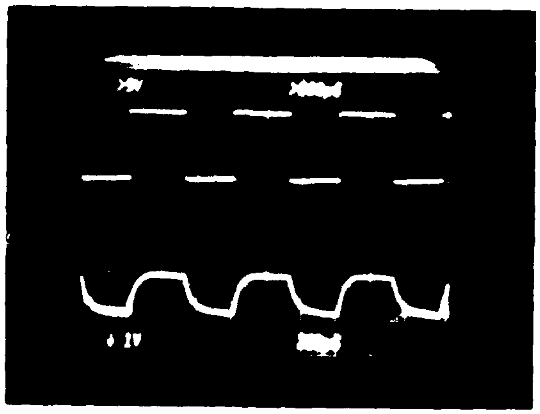


Figure 11. Steps 2 and 3 of EXCLUSIVE OR gate.

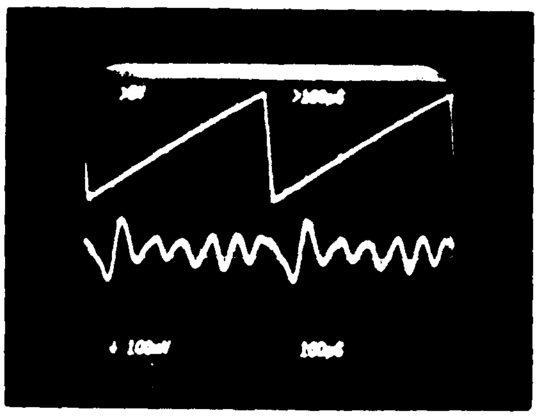


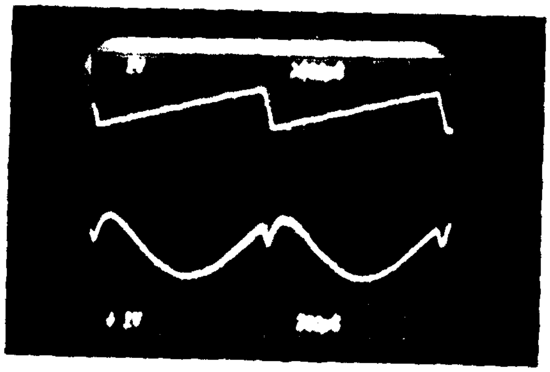
Figure 12. Step 4 of EXCLUSIVE OR gate.

Parity Generator

The even parity generator is identic[illegible]ration to the EXCLUSIVE OR gate discussed above. The odd parity generator i[illegible]entical in operation to a one-bit analog-to-digital converter. This device has been tested and reported on elsewhere.[4]

AND Gate

The AND gate also has four states in its truth table (figure 3C). Figure 13 illustrates the periodic dependence of state 1 (bias voltage only) on applied voltage. States 2 and 3 of this device are essentially the same; only one of the two interferometric modulators has an equal potential across both arms. Figure 14 shows the response of the optical AND gate with voltages applied in this manner. The fourth state is with equal potential across all four modulator arms. Figure 15 is an example of device operation under such a condition. All of the above photographs were taken using TM-polarized light. This particular device was extremely erratic when excited with TE-polarized light. The waveguides were again multi-mode in this direction. No stable oscilloscope traces were observed and no photographs could be obtained with this polarization.



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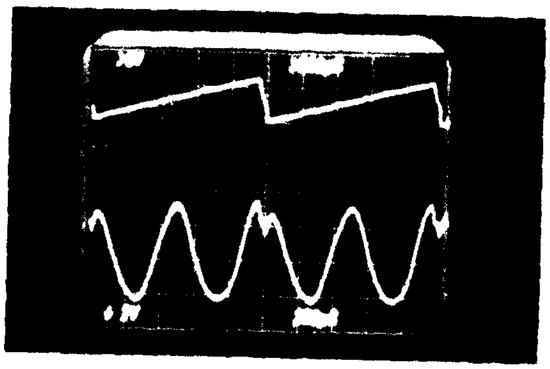

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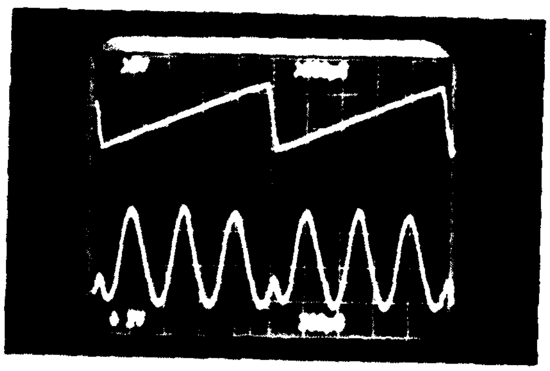

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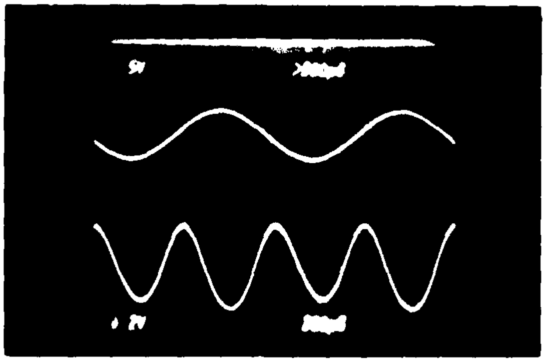
Figure 13. Response of AND gate (step 1) to increase in voltage.



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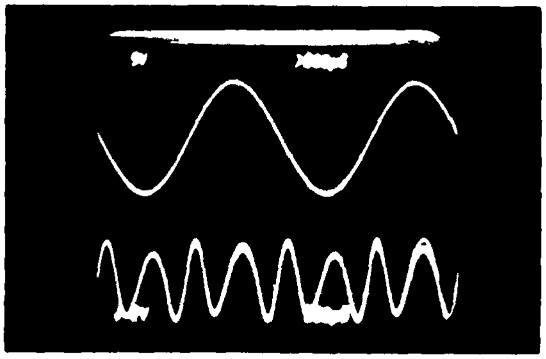

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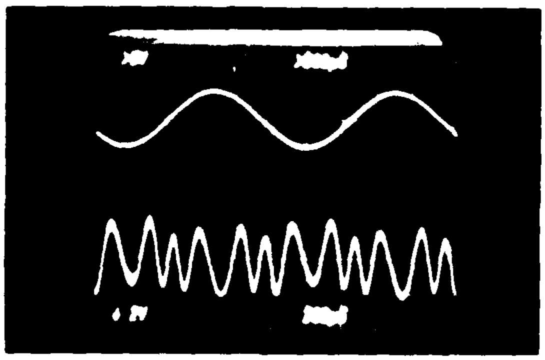

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Figure 14. Response of AND gate (steps 2 and 3) to increase in voltage.

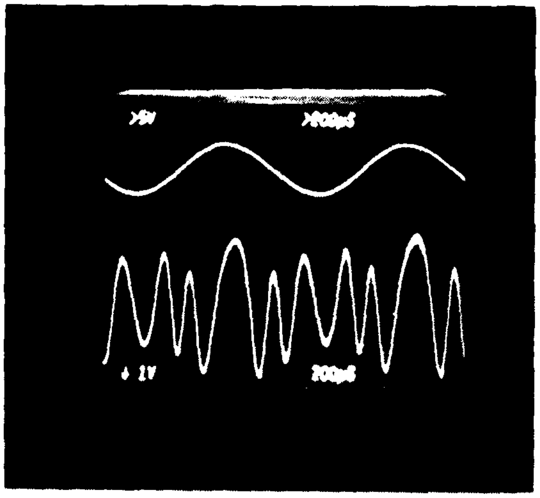

Figure 15. Step 4 of AND gate.

CONCLUSIONS

The feasibility of optical logic gates has been demonstrated using devices fabricated in Y-cut $LiNbO_3$ by titanium in-diffusion. A NOT gate, an AND gate, an EXCLUSIVE OR gate, and a parity generator have all been demonstrated using both TM-polarized light (perpendicular to substrate surface) and TE-polarized light (parallel to substrate surface) from a He-Ne laser source. Up to 100% modulation was observed in some devices. The maximum number of π radian phase shifts observed was 25 for 31-V P-P input voltage on a NOT gate, requiring only 1.2 V for a single π radian phase shift. Such electrooptic guided wave devices could likely find use in optical transmission systems where logic functions need to be performed, such as telecommunications, data acquisition and transfer, signal processing, high-speed computation, and analog-to-digital conversion. These components will be basic parts of an integrated fiber optic system used in any of the above areas.

RECOMMENDATIONS

1. Perform further studies to produce single-mode waveguides in both TE and TM directions. (Polarization independent devices.)

2. Pursue further research in the area of out-diffusion in lithium niobate. Such information could help make devices operating in the TE-mode (which requires less voltage for phase shifting) exhibit greater depths of modulation than is now being observed.

3. Redesign electrodes to require less voltage, and increase electrical efficiency of devices.

4. Examine losses at corner bends and devise new structures that are less lossy. Severe losses are experienced at angles greater than 2 or 3°, which hinders the operation of more complex structures.

5. Investigate edge finishing techniques on $LiNbO_3$ waveguides, both cleaving and polishing. Investigate a variety of polishing techniques, including diamond finishing.

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